DESIGN EXAMPLE REPORT

Title	***4.2 W Non-Isolated LED Driver LNK605DG***
Specification	85 – 265 VAC Input; 12 V, 350 mA Output
Application	LED Driver
Author	Applications Engineering Department
Document Number	DER-186
Date	September 10, 2008
Revision	1.1

Summary and Features

- Accurate primary-side constant voltage, constant current (CV/CC) controller eliminates optocoupler and all secondary side CV/CC control circuitry
  - ±5% output voltage and ±10% output current accuracy including line, load, temperature, and component tolerances
  - No current-sense resistors for maximized efficiency
  - Low part-count solution for lower cost
- Auto-restart for output short circuit and open-loop protection
- EcoSmart® – Easily meets all existing and proposed international energy efficiency standards – China (CECP) / CEC / EPA / European Commission
  - ON/OFF control provides constant efficiency to very light loads
    - No-load consumption <200 mW at 265 VAC
    - Ultra-low leakage current: <5 μA at 265 VAC input (no Y capacitor required)
  - Easy compliance to EN550015 and CISPR-22 Class B EMI
  - Meets ENERGY STAR requirements for Solid State Lighting (SSL) luminaries
  - Green package: halogen free and RoHS compliant

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Important Note:
Although this board is designed to satisfy safety isolation requirements, the engineering prototype has not been agency approved. Therefore, all testing should be performed using an isolation transformer to provide the AC input to the prototype board.

1 Introduction

This engineering report describes the design for a non-isolated, universal input, 12 V, 350 mA constant voltage/constant current (CV/CC) power supply for LED driver applications, utilizing a LNK605DG device from the LinkSwitch-II family in a tapped-inductor buck configuration.

A tapped buck topology is ideal for converters with a high ratio of voltage input to voltage output. This topology provides current multiplication on the output, making it possible to use smaller devices, or to lower dissipation losses in the MOSFET.

The tapped buck, non-isolated topology used in this design lends itself to advantages such as smaller PCB size, a smaller transformer, and greater efficiency than in the flyback topologies described in DER-184 and DER-185 (also using LinkSwitch-II devices.) The worst-case full load efficiency for this design is 80%, which is an improvement over the 74% efficiency of the previous two DER solutions. The EMI filtering is simpler in this buck topology, since there is far less common-mode noise, and lends itself to using fewer components. This design operates primarily in CC mode; CV mode only occurs when the load is disconnected, allowing the supply to operate in a safe mode, indefinitely, with the LED load disconnected.

This document contains the power supply design's specifications, schematic, bill of materials, inductor specifications, and typical performance characteristics.

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2 Prototype Photo

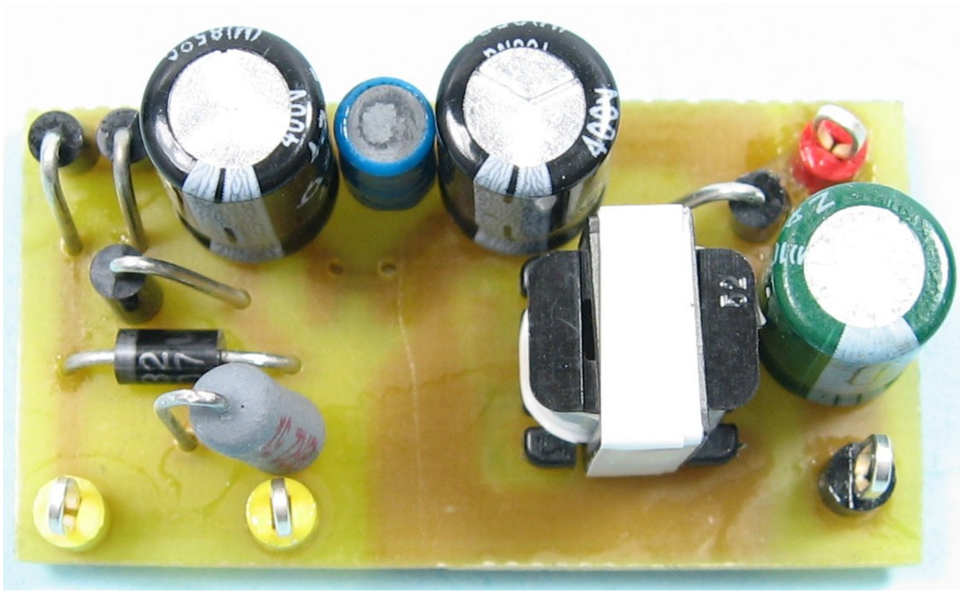

Figure 1 – Prototype Top View.

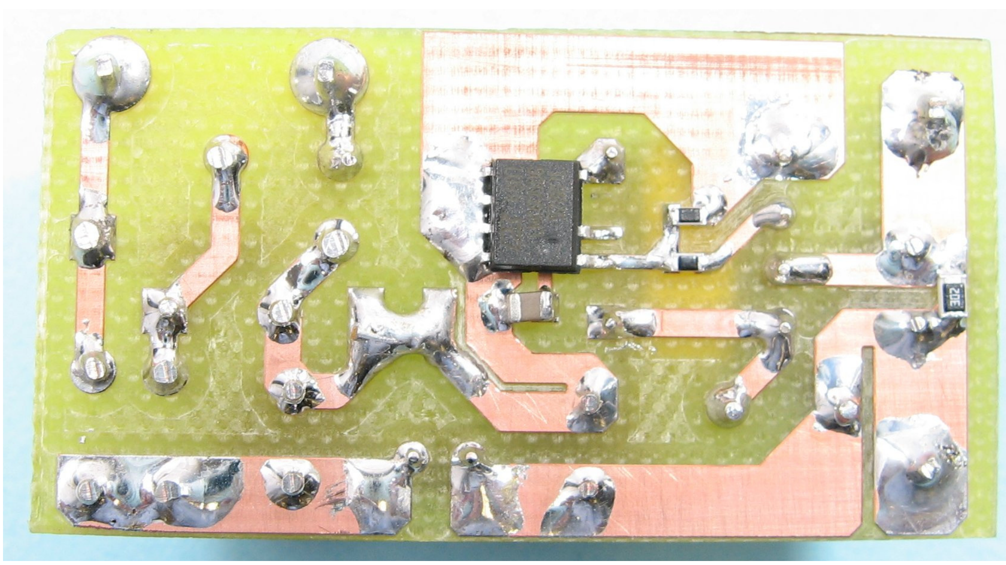

Figure 2 – Prototype Bottom View.

3 Power Supply Specification

Description	Symbol	Min	Typ	Max	Units	Comment
Input						
Voltage	V_{IN}	85		265	VAC	2 Wire – no P.E.
Frequency	f_{LINE}	47	50/60	64	Hz	
No-load Input Power (230 VAC)				300	mW	
Output						
Output Voltage 1	V_{OUT1}		12		V	Measured at the output capacitor
Output Ripple Voltage 1	$V_{RIPPLE1}$		300		mV	20 MHz bandwidth
Output Current 1	I_{OUT1}		350		mA	
Total Output Power						
Continuous Output Power	P_{OUT}		4.2		W	
Efficiency						
Full Load	η		80		%	
Environmental						
Conducted EMI		Meets CISPR22B / EN55022B				
Safety		Designed to meet IEC950, UL1950 Class II				
Surge		2			kV	1.2/50 µs surge, IEC 1000-4-5, Series Impedance: Differential Mode: 2 Ω Common Mode: 12 Ω
Ambient Temperature	T_{AMB}	-5		50	°C	Free convection, sea level

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4 Schematic

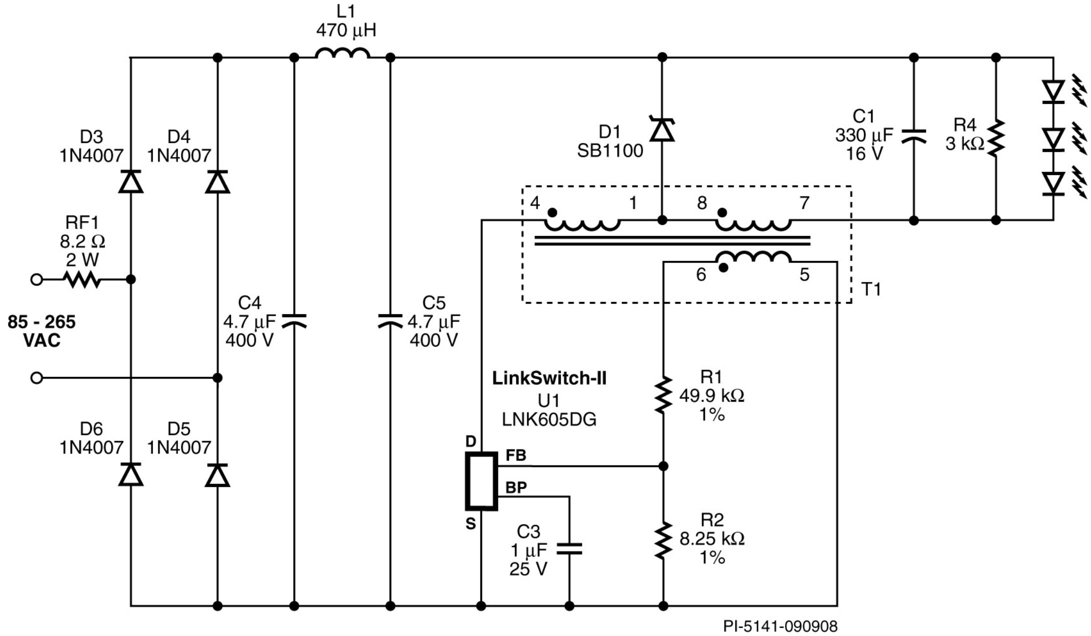

Figure 3 – Circuit Schematic.

5 Circuit Description

This circuit uses the LinkSwitch-II family product LNK605DG in a non-isolated tapped buck power-supply configuration.

The LNK605DG device (U1) incorporates a power switching device, an oscillator, a CV/CC control engine, and startup and protection functions all in one IC. The integrated 700 V MOSFET allows sufficient voltage margin for universal input AC applications. The power supply delivers full output current during the maximum forward voltage drop of the LED.

The LNK605DG's IC package provides extended distance between high and low voltage pins (both at the package and the PCB), which is required in very humid or highly polluted environments to prevent arcing and to further improve reliability.

5.1 LNK605DG Operation

The LNK605DG monolithically integrates a 700 V power MOSFET switch and ON/OFF control. The constant voltage (CV) regulation provides ±5% accuracy. The CV function is not needed during normal operation in this application. The CV feature provides inherent output over-voltage protection in case any LEDs fail open circuit or if the load becomes disconnected. Beyond the maximum power point, the switching frequency is reduced to provide a constant output current at an accuracy of ±10%. This makes the LNK605DG ideal for driving LEDs, which require a constant current level for consistent light output and long life operation. In addition, internal compensation allows the ±5% voltage and ±10% current accuracies to be met across component tolerances, device tolerances, temperature, and line input voltage variations.

The LNK605DG also provides a sophisticated range of protection features such as auto-restart and thermal shutdown. Auto-restart is triggered by fault conditions which include an open feedback loop or a shorted output. Accurate hysteretic thermal shutdown ensures safe average PCB temperatures under all conditions.

5.2 Input Filter

Diodes D3, D4, D5, and D6 rectify the AC input. The resulting DC is filtered by the bulk storage capacitors, C4 and C5. Inductor L1 and capacitors C4 and C5 form a pi (π) filter, which attenuates conducted differential-mode EMI noise. This configuration enables easy compliance to EMI standard EN55015 class B, with 10 dB of margin. Fusible, flameproof resistor RF1 acts as a fuse and should be rated to withstand the instantaneous dissipation when the supply is first connected to the AC. Wire-wound or oversized metal-film resistors work well for this purpose.

5.3 Tapped Buck Operation

Figure 3 shows the schematic for a tapped buck converter, based on the LNK605DG. A power supply using a tapped buck topology operates in a way very similar to one with a buck topology. When the switch turns on (closes), current ramps up and flows through

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the complete inductor (pin 7 to pin 4), and through the load (the LEDs). The load current is filtered by C1 to remove the switching component from the current waveform. Diode D1 is reverse-biased and so does not conduct during this time. The current continues to ramp up until it reaches the current limit value, which causes the switch to turn off (open).

When the switch turns off, the energy in the input section of inductor (T1) couples through to the output section (pin 7 to pin 8). The peak current in the output winding steps up by a factor of 4.6 (equal to the ratio of total inductor turns to the output section turns), keeping the total ampere-turns constant. This stepped (magnified) current flows out of the output winding, through free-wheeling diode D1, and back through the load. (See Figure 16 though Figure 19.) Due to non-ideal coupling between the tapped windings, some of the stored energy does not couple to the output winding.

The leakage energy in the input section of T1 (pin 4 to pin 1) causes a voltage spike at turn off. This spike is limited by the intra-winding capacitance of T1. This parasitic capacitance is sufficient to keep the voltage spike from exceeding the BV_{DSS} (700 V) of the MOSFET internal to U1.

The voltage stress on the switch in this design is equal to that in a Flyback converter using a transformer with the same turns ratio. The chosen turns ratio ensures the circuit operates in discontinuous mode (DCM) at low line (85 VAC). This ratio (the inductor ratio) can be calculated as

$$Inductor\ Ratio = \frac{Total\ Inductor\ turns}{Output\ Winding\ Turns} = \frac{124}{27} = 4.6$$

5.4 Output Regulation

The LNK605DG regulates output using ON/OFF control for CV regulation, and frequency control for constant current (CC) regulation. Feedback resistors R1 and R2 have 1% tolerance values to assist accurately centering both the nominal output voltage and the CC regulation threshold. The CV feature provides output over-voltage protection (OVP) in case any LEDs have open-circuit failures. This design operates primarily in CC mode, but it goes into CV mode below full load, or when the load is disconnected.

A feedback winding tracks and regulates the output. This winding must be closely coupled to the tapped section (the section of winding between pin 7 and pin 8) of T1.

Traversing from no load to full load, the controller within the LNK605DG first operates in CV mode. Upon detecting the maximum power point, the controller enters CC mode.

While the LNK605DG operates in the CV region, it regulates the output voltage by adjusting the ratio of enabled cycles to disabled switching cycles. This also optimizes the efficiency of the converter over the entire load range. As the load current increases, the current limit is increased and fewer and fewer cycles are skipped.

At the point where no switching cycles are skipped (concurrent to the maximum power point) the controller within the LinkSwitch-II transitions into CC mode. A further increase in the demand for load current causes the output voltage to drop. This drop in output voltage is reflected on the FB pin voltage. In response to the voltage reduction on the FB pin, the switching frequency is reduced to achieve constant output current.

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6 PCB Layout

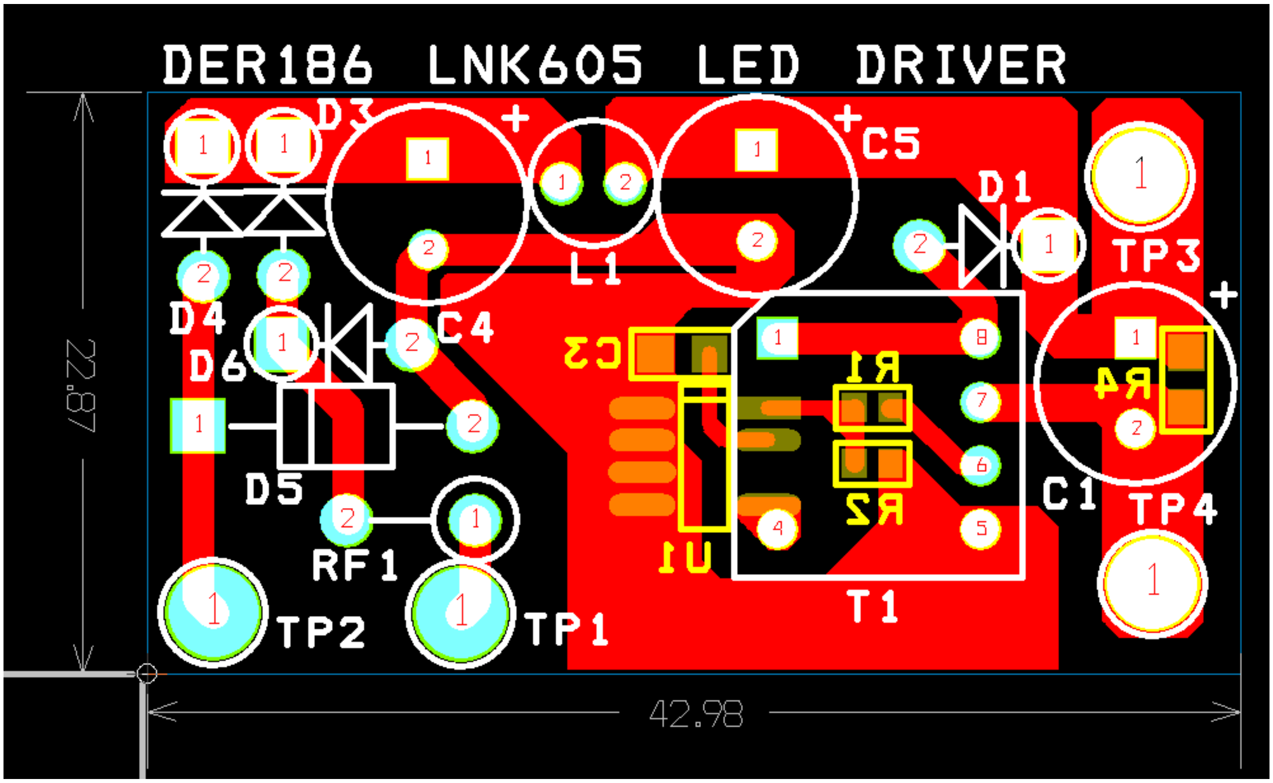

Figure 4 – PCB Layout (43mm x 23mm).

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7 Bill of Materials

Item	Qty	Ref Des	Description	Mfg	Mfg Part Number
1	1	C1	330 µF, 16 V, Electrolytic, Very Low ESR, 72 mOhm, (8 x 11.5)	Nippon Chemi-Con	EKZE160ELL331MHB5D
2	1	C3	1 µF, 25 V, Ceramic, X7R, 0805	Panasonic	ECJ-2FB1E105K
3	2	C4 C5	4.7 µF, 400 V, Electrolytic, (8 x 11.5)	Taicon Corporation	TAQ2G4R7MK0811MLL3
4	1	D1	100 V, 1 A, Schottky, DO-41	Vishay	SB1100
5	4	D3 D4 D5 D6	1000 V, 1 A, Rectifier, DO-41	Vishay	1N4007-E3/54
6	1	L1	470 µH, 0.3 A, 5.5 x 10.5 mm	Tokin	SBC1-471-301
7	1	R1	49.9 kΩ, 1%, 1/16 W, Metal Film, 0603	Panasonic	ERJ-3EKF4992V
8	1	R2	8.25 kΩ, 1%, 1/16 W, Metal Film, 0603	Panasonic	ERJ-3EKF8251V
9	1	R4	3 kΩ, 5%, 1/8 W, Metal Film, 0805	Panasonic	ERJ-6GEYJ302V
10	1	RF1	8.2 Ω, 2 W, Fusible/Flame Proof	Vitrohm	CRF253-4 5T 8R2
11	1	T1	Bobbin, EE10, Vertical, 8 pins	Hical Magnetics	101
12	2	TP1 TP4	Test Point, BLK,THRU-HOLE MOUNT	Keystone	5011
13	1	TP2	Test Point, WHT,THRU-HOLE MOUNT	Keystone	5012
14	1	TP3	Test Point, RED,THRU-HOLE MOUNT	Keystone	5010
15	1	U1	LinkSwitch-II, LNK605DG, CV/CC, SO-8C	Power Integrations	LNK605DG

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8 Tapped-inductor Specifications

8.1 Electrical Diagram

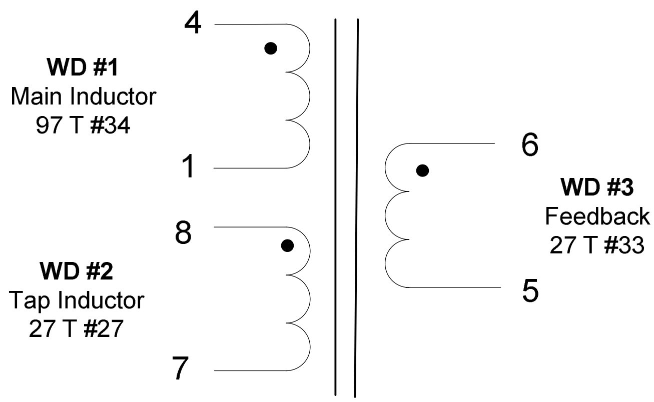

Figure 5 – Transformer Electrical Diagram.

8.2 Electrical Specifications

Electrical Strength	1 second, 60 Hz, from Primary to Secondary	N/A
Main Inductance	Pins 4 - 7, short Pin 1 and Pin 8 together, measured at 80 kHz, 0.4 VRMS	1.32 mH, ±10%
Resonant Frequency	Pins 4 - 7, Pin 1 and Pin 8 are shorted together with all other windings open	1.1 MHz
Primary Leakage Inductance	Pin 4 to pin 1, Pin 7 and Pin 8 are shorted together	18 μH

8.3 Materials

Item	Description
[1]	Core: PC44, gapped for A_L of 86.3 nH/t^2
[2]	Bobbin: Horizontal 8 pin, EE10
[3]	Magnet Wire: #34 AWG
[4]	Magnet Wire: #27 AWG
[5]	Magnet Wire: #33 AWG
[6]	Tape, 3M 1298 Polyester Film, 2.0 Mils thick, 7.0 mm wide
[7]	Varnish

8.4 Tapped Inductor Build Diagram

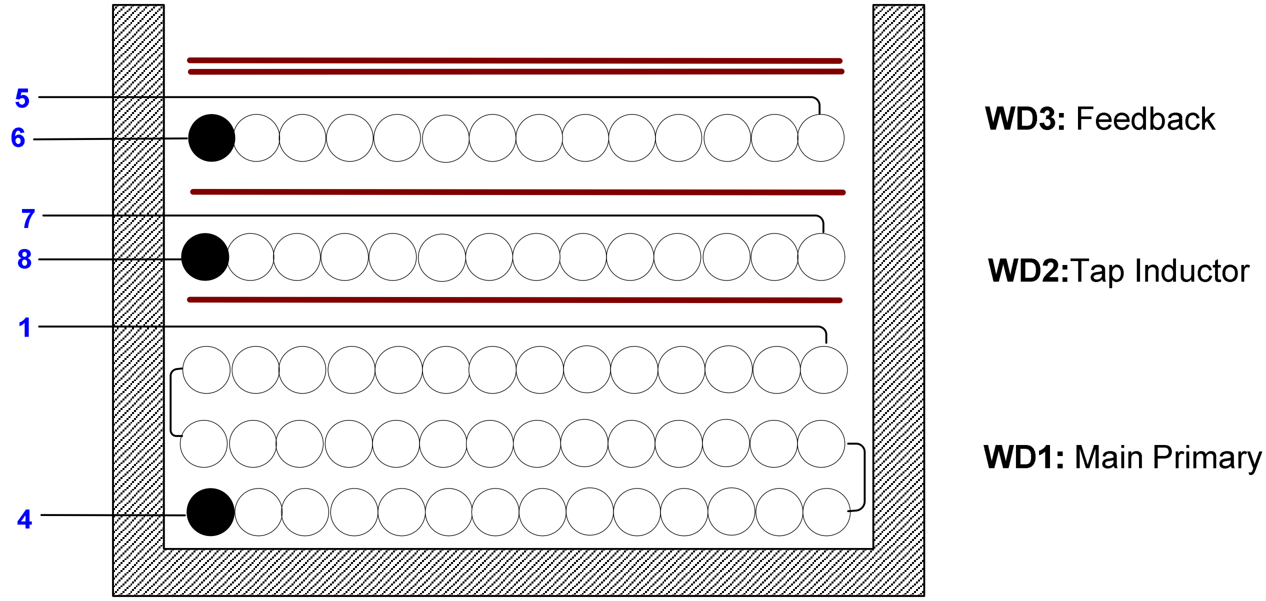

Figure 6 – Transformer Build Diagram.

8.5 Winding Instruction

WD1 Main Winding	Primary Pin side of the bobbin oriented to right hand side. Start at pin 4. Wind 97 turns of item [3] in three layers. Wind with tight tension across bobbin evenly. End at pin 1.
Insulation	1 Layer of tape [6] for insulation.
WD #2 Tap Winding	Start at pin 8. Wind 27 turns of item [4] in two layers. Terminate on pin 7. Wind with tight tension and spread turns across bobbin evenly.
Insulation	1 layer of tape [6] for basic insulation.
WD #3 Feedback Winding	Starting at pin 6, wind 27 turns of item [5] in one layer. Finish on pin 5. Wind with tight tension and spread turns across bobbin evenly.
Insulation	2 layers of tape [6] for basic insulation.
Core Assembly	Gap core and assemble and secure core halves.
Varnish	Dip varnish assembly with item [7].

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9 Design Spreadsheet

ACDC_LinkSwitch-II_Tapped Buck_051308; Rev.0.3; Copyright Power Integrations 2008	INPUT	INFO	OUTPUT	UNIT	ACDC_LinkSwitch-II_Tapped Buck_051308_Rev0-3.xls; LinkSwitch-II Discontinuous Tapped Buck Design Spreadsheet
ENTER APPLICATION VARIABLES					Customer
VACMIN	85			V	Minimum AC Input Voltage
VACMAX	265			V	Maximum AC Input Voltage
fL	50			Hz	AC Mains Frequency
VO	12			V	Output Voltage of LED strings
IO	0.35			A	Output Current driving LED strings
Power			4.20	W	Continuous Output Power
n	0.8		0.80		Efficiency Estimate at output terminals. Under 0.7 if no better data available
Z			0.50		Z Factor. Ratio of secondary side losses to the total losses in the power supply. Use 0.5 if no better data available
tC			3.50	ms	Bridge Rectifier Conduction Time Estimate
CIN	10			uF	Input Capacitance
DC INPUT VOLTAGE PARAMETERS					
VMIN			87.32	V	Minimum Input DC bus voltage
VMAX			374.77	V	Maximum Input DC bus voltage
ENTER LinkSwitch-II VARIABLES					
Chosen Device	**LNK 605**		LNK605		Chosen LinkSwitch-II device
Package	**DG**		DG		Select package (PG, GG or DG)
ILIMITMIN			0.30	A	Minimum Current Limit
ILIMITTYP			0.31	A	Typical Current Limit
ILIMITMAX			0.35	A	Maximum Current Limit
FS	80		80.00	kHz	Typical Device Switching Frequency at maximum power
VDS			10.00	V	LinkSwitch-II on-state Drain to Source Voltage
VD			0.50	V	Output Winding Diode Forward Voltage Drop
DESIGN PARAMETERS					
DCON			7.46	us	Output diode conduction time
TON			4.71	us	LinkSwitch-II On-time (calculated at minimum inductance)
TDEAD			0.32	us	LinkSwitch-II dead time when both the switch and diode are NOT conducting (calculated at minimum inductance)
ENTER INDUCTOR CORE/CONSTRUCTION VARIABLES					
Core Type					
Core	**EE10**		EE10		Enter Transformer Core
Bobbin			EE10_BOBBIN		Generic EE10_BOBBIN
AE			12.10	mm^2	Core Effective Cross Sectional Area
LE			26.10	mm^2	Core Effective Path Length
AL			850.00	nH/turn^2	Ungapped Core Effective Inductance
BW			6.60	mm	Bobbin Physical Winding Width
INDUCTOR DESIGN PARAMETERS					
LPMIN			1263.81	uH	Minimum Inductance (Includes inductance of input and output winding)
LPTYP			1327.01	uH	Typical inductance (Includes inductance of input and output winding)
LP_TOLERANCE	5		5.00		Tolerance in inductance
NL_TOTAL			124.00		Total number of turns (Includes input and output winding turns). To adjust Total number of turns change BM_TARGET
ALG			86.30	nH/turn^	Gapped Core Effective Inductance

				2	
BM_TARGET	2750		2750.00	Gauss	Target Flux Density
BM			2741.75	Gauss	Maximum Operating Flux Density (calculated at nominal inductance), BM < 3000 is recommended
BP			3217.79	Gauss	Peak Operating Flux Density (calculated at maximum inductance and max current limit), BP < 3300 is recommended
BAC			1370.87	Gauss	AC Flux Density for Core Loss Curves (0.5 X Peak to Peak)
ur			145.90		Relative Permeability of Ungapped Core
LG			0.17	mm	Gap Length (LG > 0.1 mm)
INDUCTOR_RATIO	0.215		0.22		Ratio of Output windng turns to Total inductor turns. Adjust ratio to ensure discontinuous operation
Input Section					Section of winding that conducts only during ON time of the LINKSwitch-II
NL_INPUT					Number of turns in Input section.
AWG	31		31.00		Primary Wire Gauge (Rounded to next smaller standard AWG value)
L			3.92		Number of Layers (Input section)
CMA		*Info*	850.79		!!! Info. CMA is on the higher side of recommendation but design will work. Consider increasing AWG
Output Section					Section of winding that conducts both when the Linkswitch-II is ON and OFF.
NL_OUTPUT			27.00		Number of Turns in Output winding. To adjust number of turns change INDUCTOR_RATIO
AWG_OUTPUT	32		32.00		Output Winding Wire Gauge (Rounded to next smaller standard AWG value)
L_OUTPUT			0.99		Number of Layers (Output winding)
CMA_OUTPUT		*Info*	100.76		!!! Info. CMA is less than 200 and may cause overheating of the primary winding. This maybe acceptable if number of turns is low. Reduce AWG_OUTPUT

CURRENT WAVEFORM SHAPE PARAMETERS			
DMAX	0.38		Maximum duty cycle measured at VMIN
IAVG	0.06	A	Input Average current
IP	0.30	A	Peak primary current
ID_PK	1.59	A	
ISW_RMS	0.09	A	Switch RMS current
ID_RMS	0.64	A	Freewheeling Diode RMS current
IL_RMS	0.09	A	Inductor - Input section RMS current
IL_TAP_RMS	0.64	A	Inductor - Output winding section RMS current
IR	0.30	A	Primary ripple current

FEEDBACK WINDING PARAMETERS			
NFB	27.00		Feedback winding turns
VFLY	12.00	V	Voltage across diode at turn off
VFOR	16.40	V	Voltage across Output winding of inductor when switch is on.
RUPPER	49.03	k-ohm	Upper resistor in Feedback resistor divider
RLOWER	9.81	k-ohm	Lower resistor in resistor divider

VOLTAGE STRESS PARAMETERS			
VDRAIN	529.88	V	Maximum Drain Voltage Estimate (Assumes 100 V leakage spike)
PIVS	81.60	V	Output Rectifier Maximum Peak Inverse Voltage

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10 Performance Data

All measurements performed at room temperature, 60 Hz input frequency.

10.1 Efficiency with LED Load – Full Load

This data was taken using three 350 mA, 3.5 V LEDs connected in a series string.

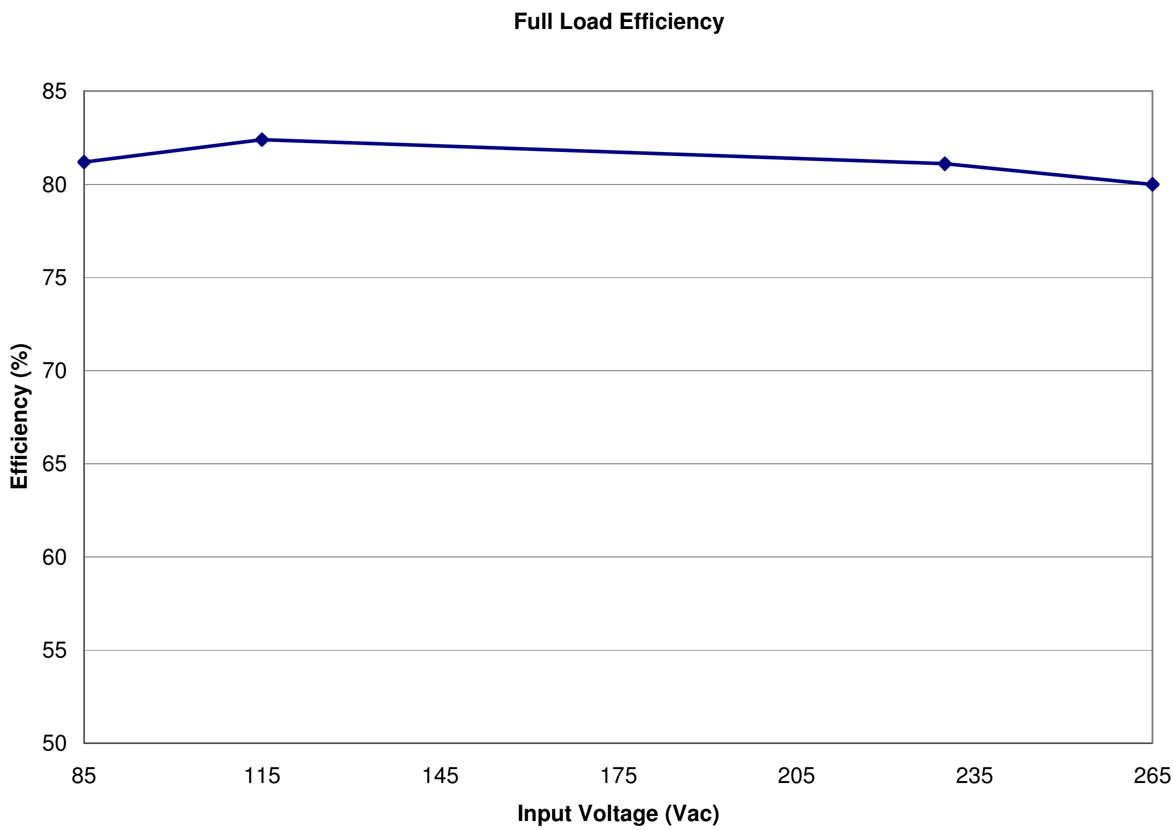

Figure 7 – Full-load Efficiency vs Input Voltage.

10.2 No-load Input Power

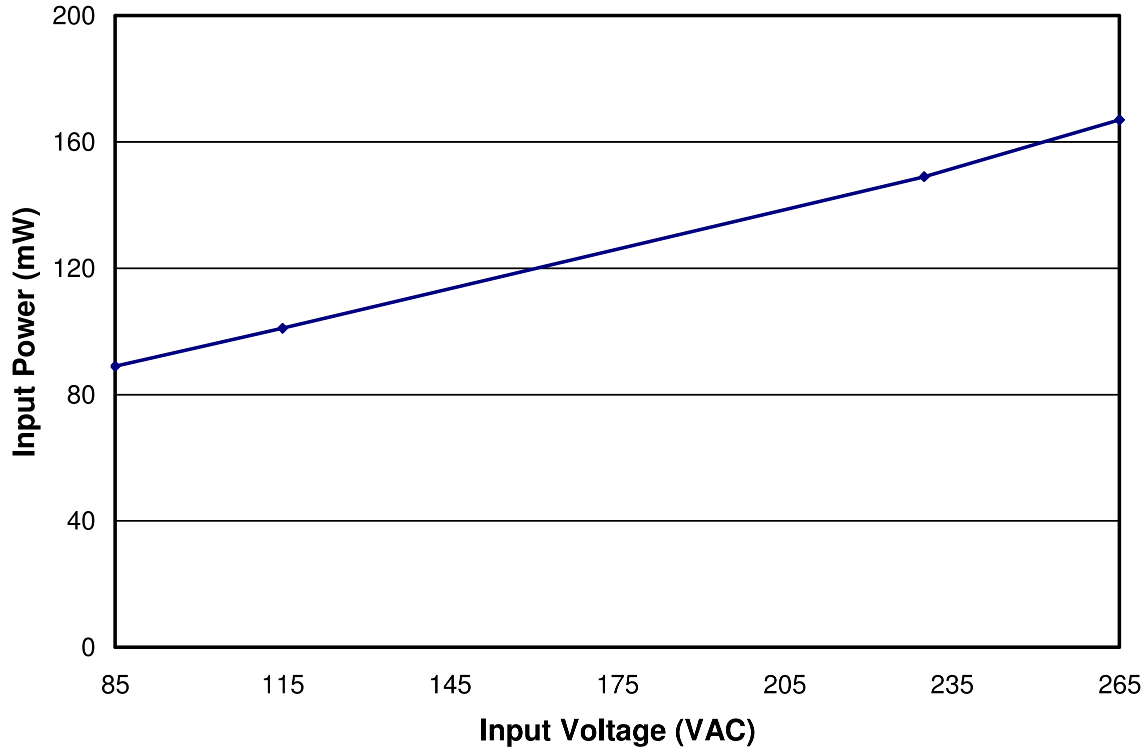

Figure 8 – No-load Power Consumption.

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10.3 Output Characteristics

The output voltage and current were measured at the board. This data was taken at room temperature.

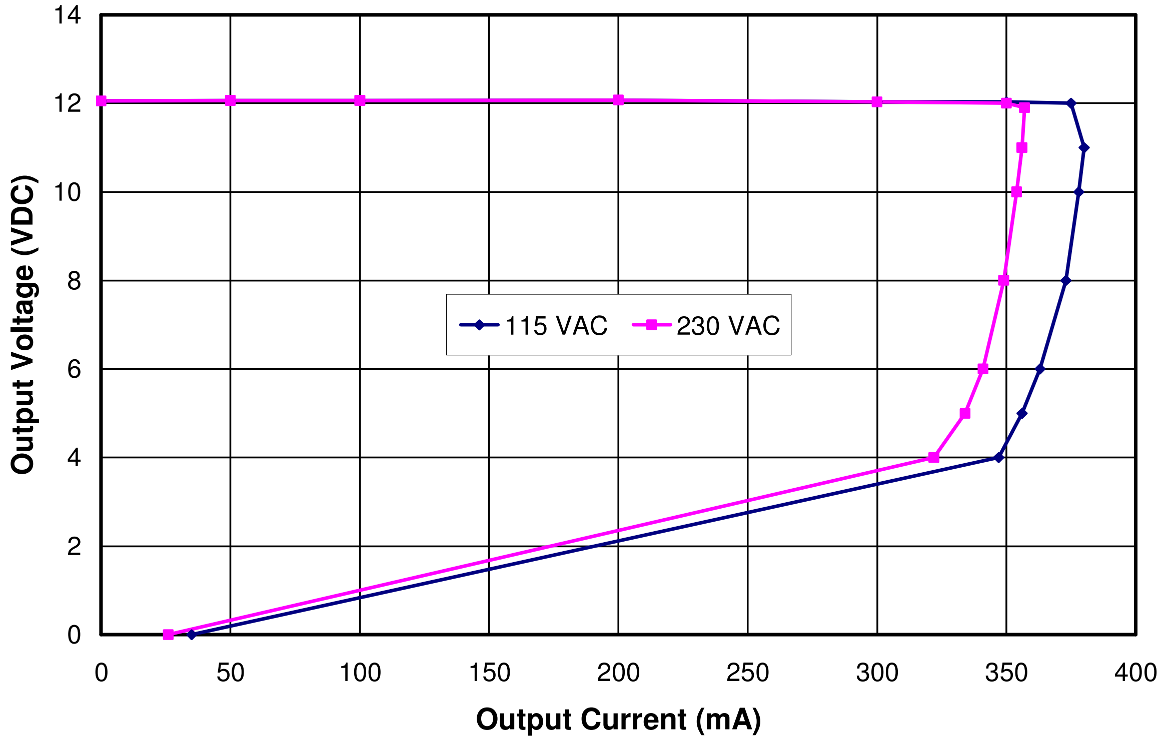

Figure 9 – Output Characteristic.

10.4 Thermal Performance

Thermal performance was measured by putting the power supply inside a plastic enclosure. The enclosure was placed inside a box, protected from air flow. An ambient thermal probe was placed about 1 inch away from the enclosure, not touching anything. A thermocouple was soldered to U1 at the Source Pin, and another was soldered to D1. A third thermocouple was taped to T1.

Results:

Input Voltage	**85 VAC**	**265 VAC**
Ambient	**50.5 °C**	**50.5 °C**
U1	86.8 °C	91.9 °C
T1	72.3 °C	74.2 °C
D1	74.8 °C	73.9 °C

10.5 Output Ripple Measurements

10.5.1 Ripple Measurement Technique

For DC output ripple measurements, use a modified oscilloscope test probe to reduce spurious signals. Details of the probe modification are provided in figures below.

Tie two capacitors in parallel across the probe tip of the 4987BA probe adapter. Use a 0.1 µF/50 V ceramic capacitor and a 1.0 µF/50 V aluminum-electrolytic capacitor. The aluminum-electrolytic capacitor is polarized, so always maintain proper polarity across DC outputs.

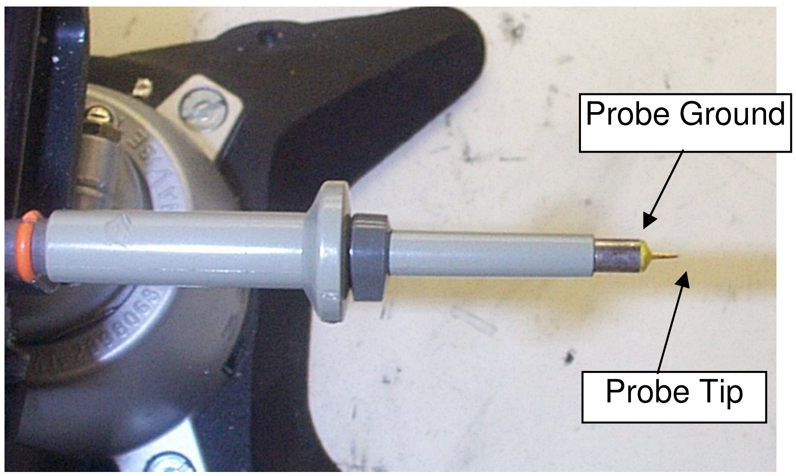

Figure 10 – Oscilloscope Probe Prepared for Ripple Measurement. (End Cap and Ground Lead Removed)

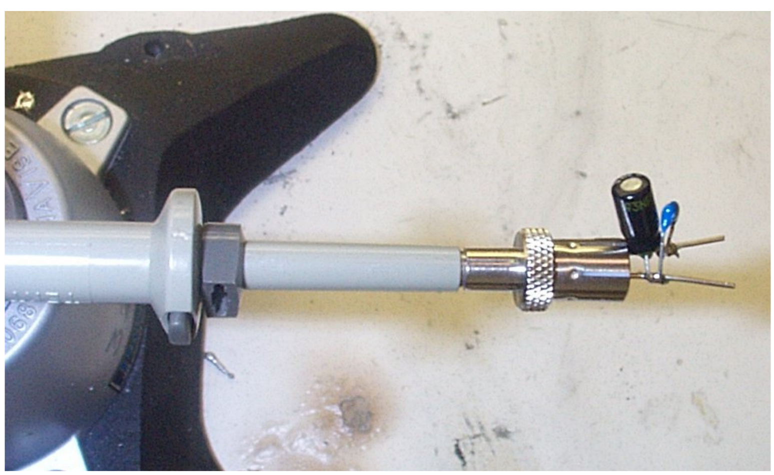

Figure 11 – Oscilloscope Probe with Probe Master 4987BA BNC Adapter. (Modified with wires for probe ground for ripple measurement, and two parallel decoupling capacitors added)

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10.5.2 Measurement Results

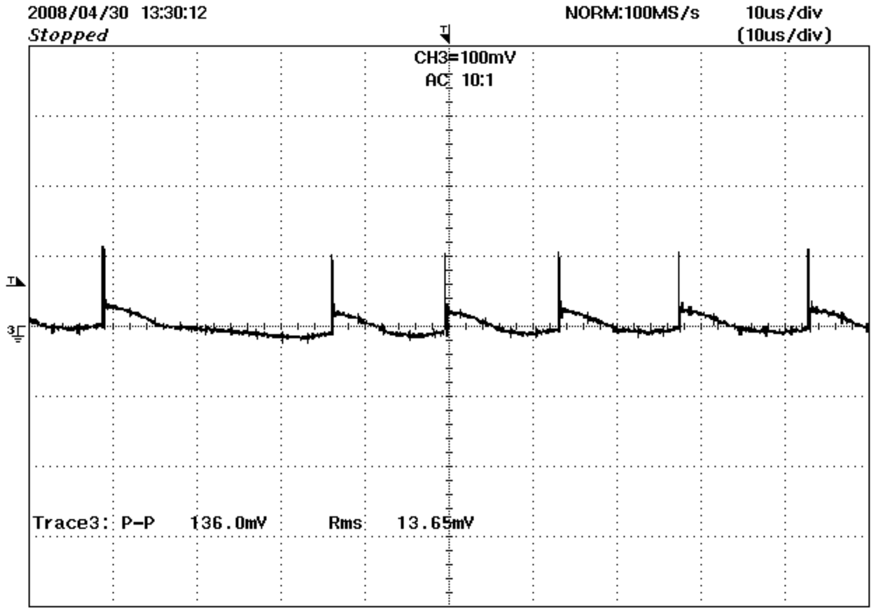

Figure 12 – Output Ripple and Noise at 115 VAC Input with LED Load.

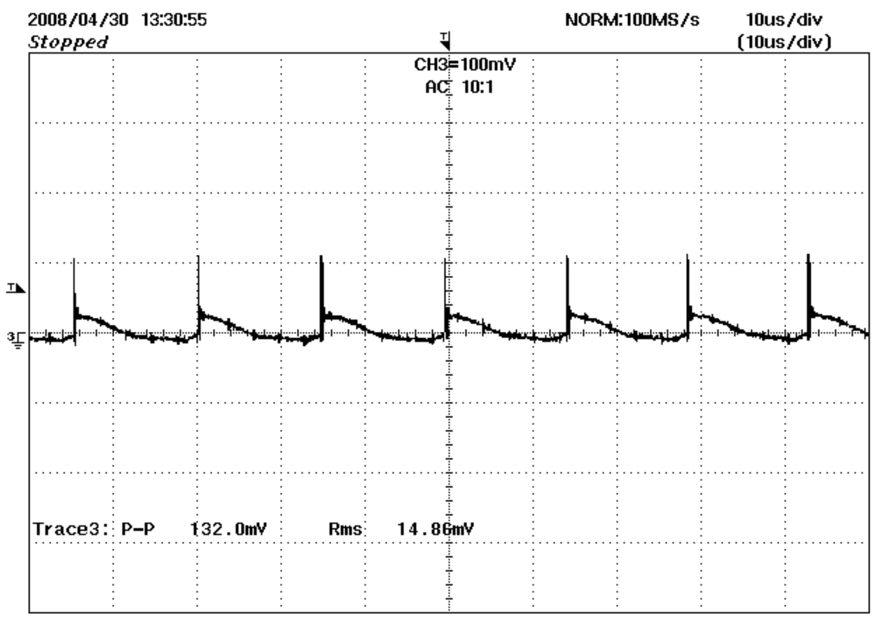

Figure 13 – Output Ripple and Noise at 230 VAC Input with LED Load.

11 Output Current Ripple

11.1 Load Current Ripple

The following oscillograms show the AC component in the load current. LEDs were used as the load.

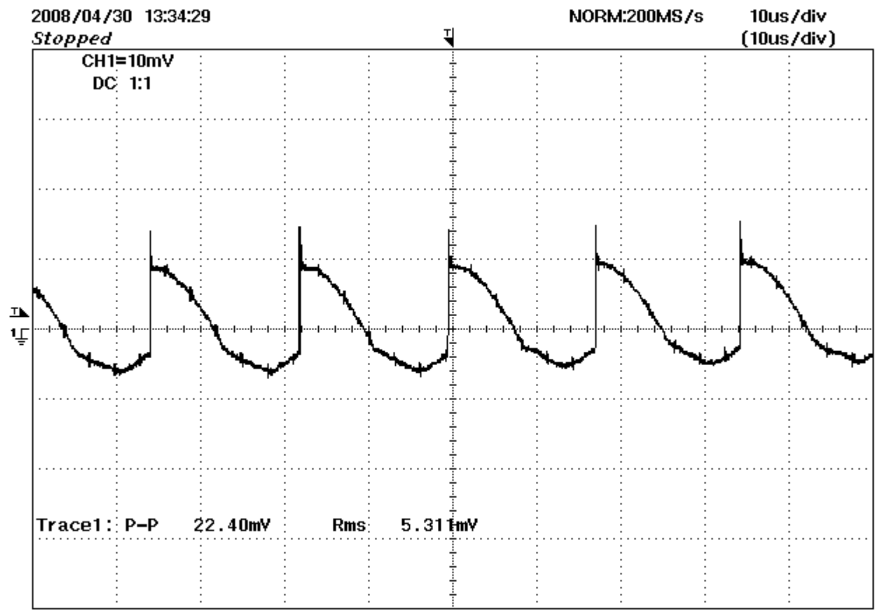

Figure 14 – Output Current Ripple at 115 VAC Input. Current: 10 mA/div, 10 µs/div.

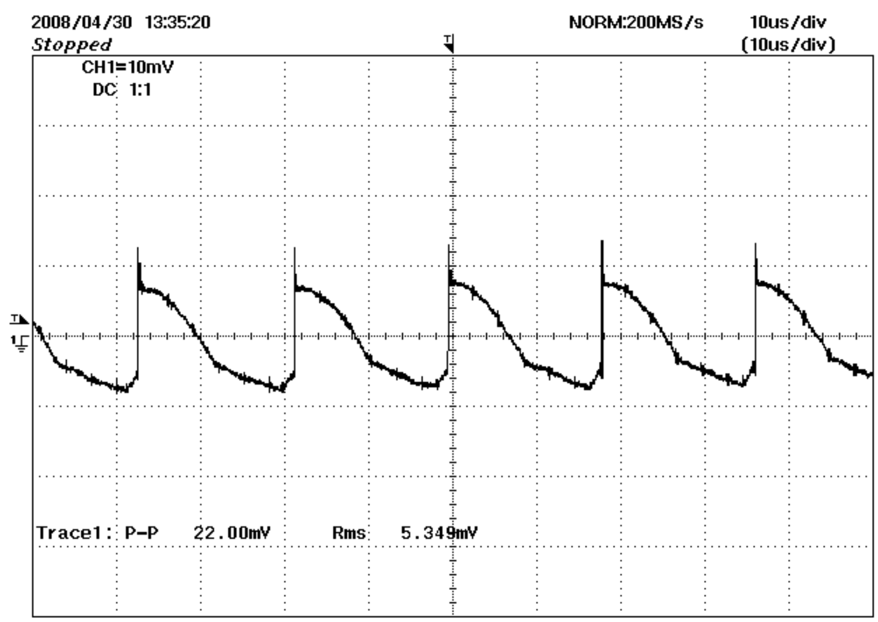

Figure 15 – Output Current Ripple at 230 VAC. Current: 10 mA/div, 10 µs/div.

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11.2 Inductor Current

The inductor current over the entire switching cycle is shown in the following four oscillograms. 3 series-connected LEDs were used as the load. At turn off the current in the inductor increases by a factor of 4.6 (corresponding to the turns ratio).

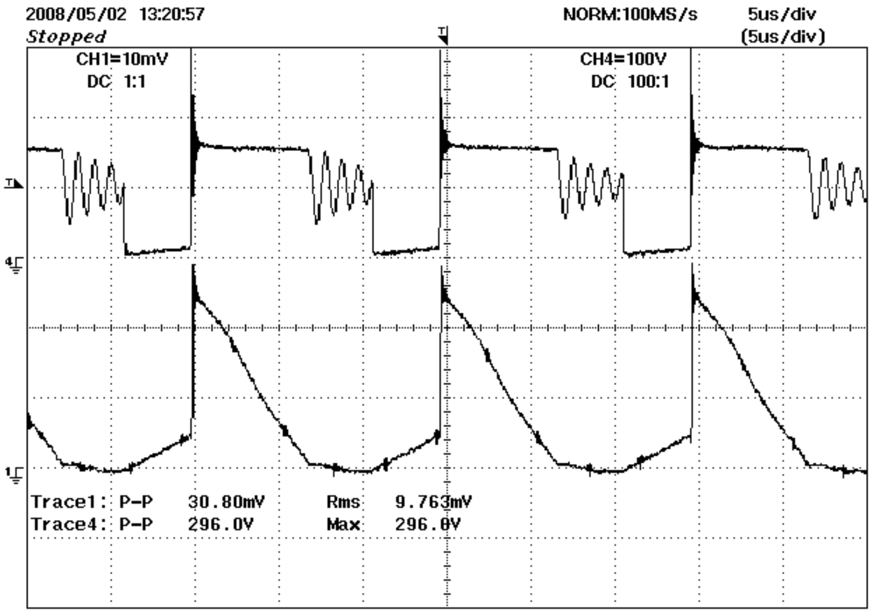

Figure 16 – Inductor Current at 85 VAC. 0.5 A/div.

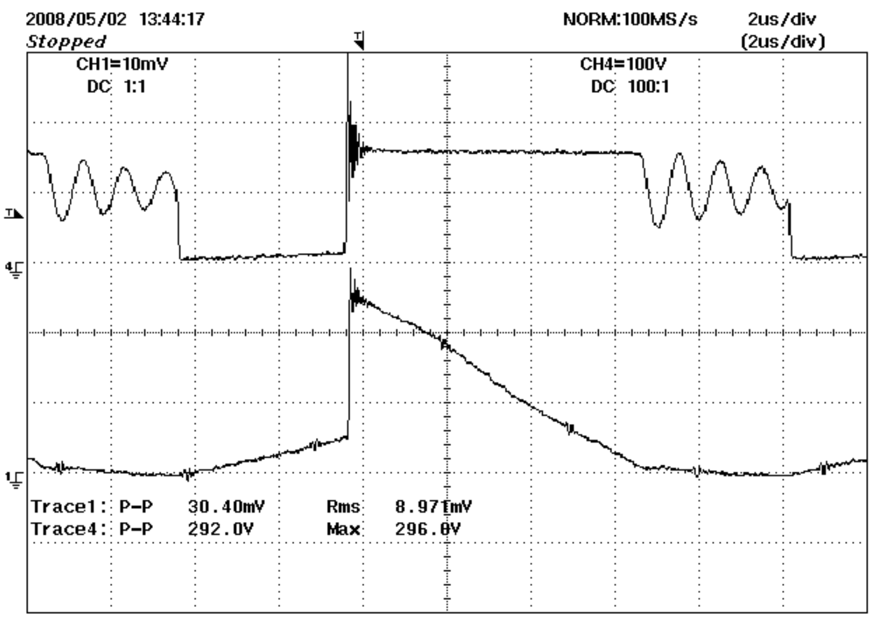

Figure 17 – Inductor Current at 85 VAC. 0.5 A/div.

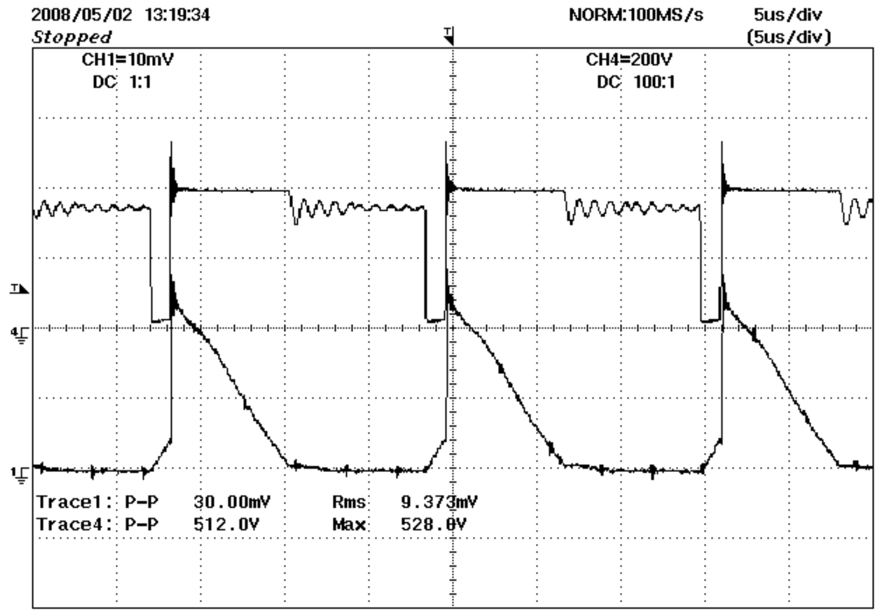

Figure 18 – Inductor Current at 265 VAC. 0.5 A/div.

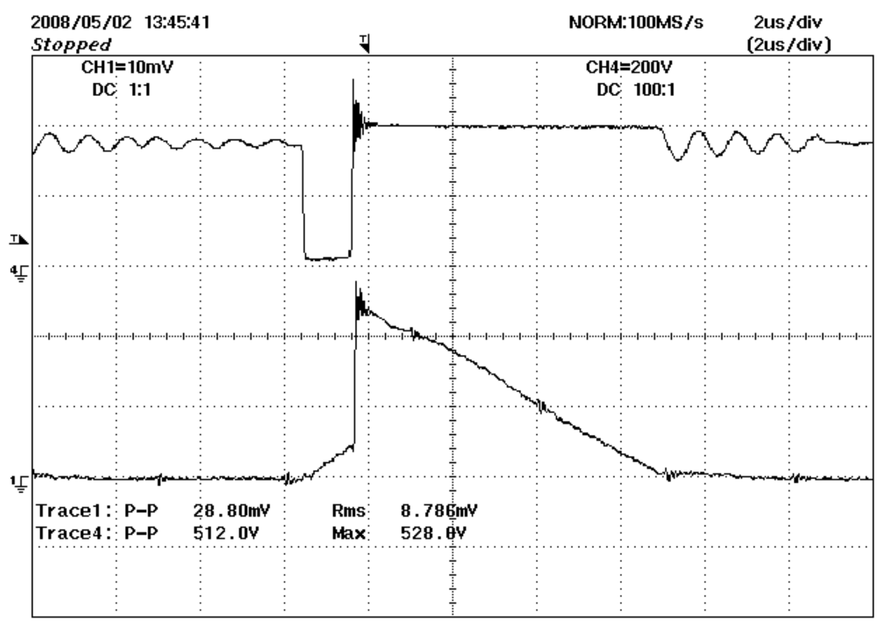

Figure 19 – Inductor Current at 265 VAC. 0.5 A/div.

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12 Waveforms

12.1 Output Voltage Startup Profile

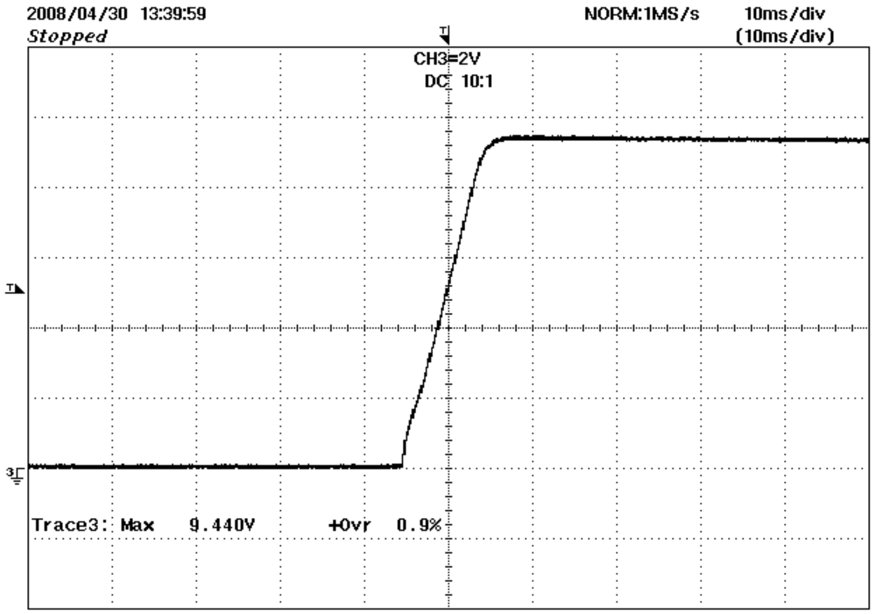

Figure 20 – Output Voltage at Startup (115 VAC Input), Full Load. 2 V/div and 10 ms/div.

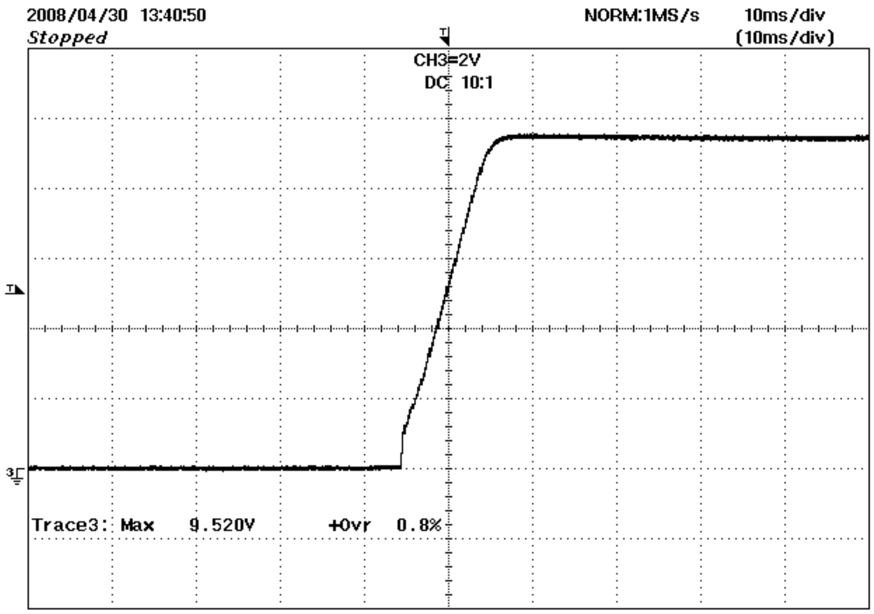

Figure 21 – Output Voltage at Startup (230 VAC Input), Full Load. 2 V/div and 10 ms/div.

12.2 Output Current Startup Profile

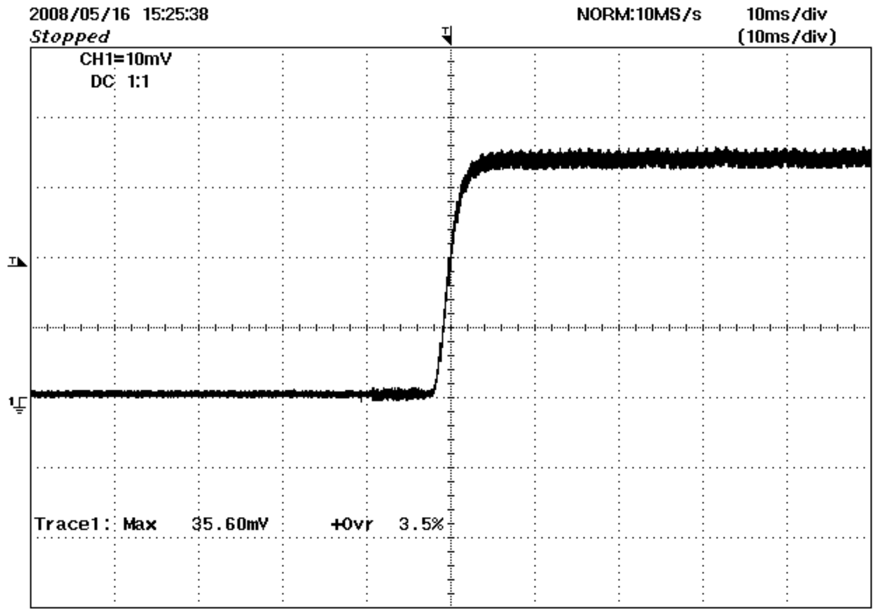

Figure 22 – LED Current at Startup (115 VAC), Full Load. 100 mA/div and 10 ms/div.

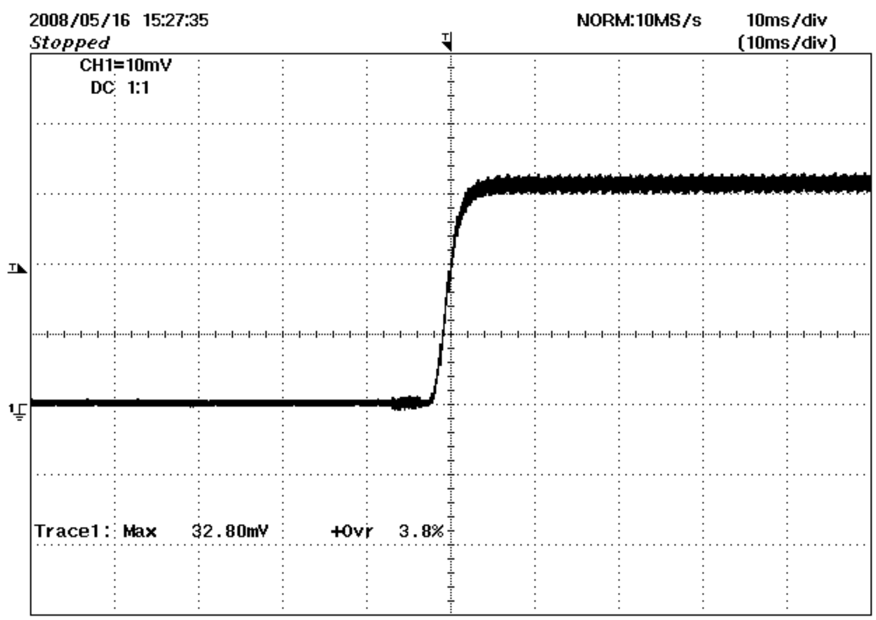

Figure 23 – LED Current at Startup (230 VAC), Full Load. 100 mA/div and 10 ms/div.

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12.3 Drain Voltage and Current

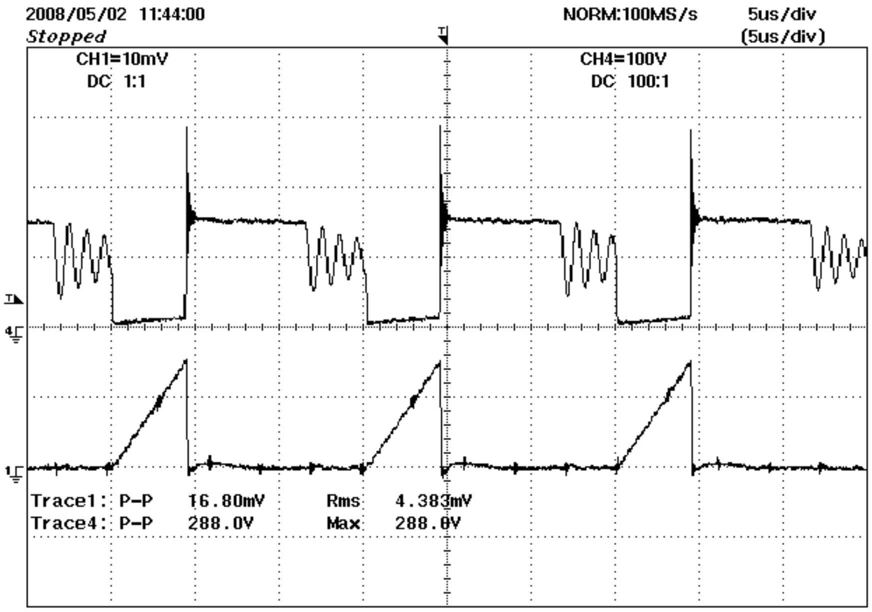

Figure 24 – Drain Voltage at 85 VAC Input. Current: 0.2 A/div.

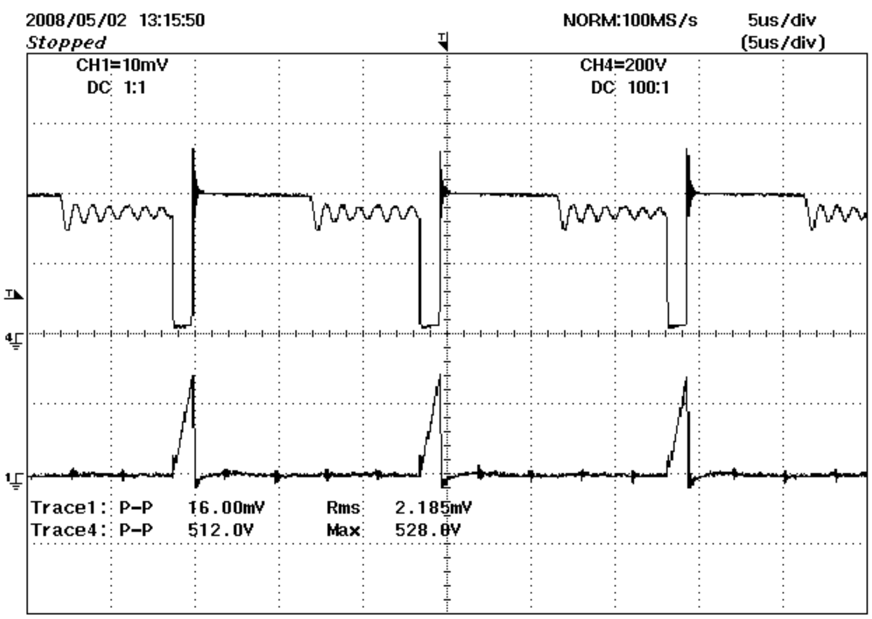

Figure 25 – Drain Voltage at 265 VAC Input. Current: 0.2 A/div.

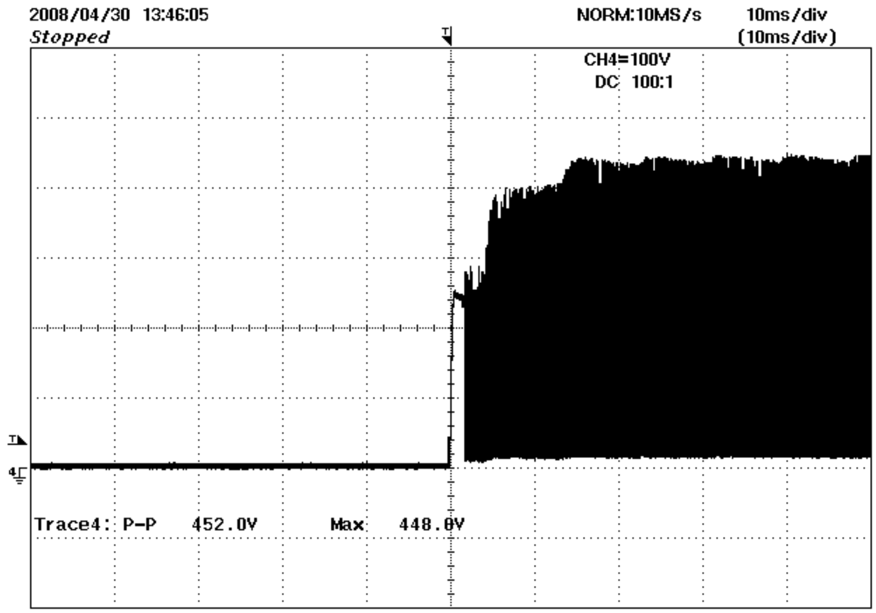

Figure 26 – Drain Voltage During Startup at 265 VAC. 100 V/div and 10 ms/div.

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13 Transient Protection

Energy Star line-transient protection requires immunity to 7 strikes of a 100 kHz ring wave, 2.5 kV level, for both common mode and differential mode.

The following tests were performed at 230 VAC input, at both 90 ° and 270 ° phase.

Differential Mode

Phase	Voltage	Current	Results
90 Degree	2.5 kV	500 A	Pass
270 Degree	2.5 kV	500 A	Pass

Common Mode

Phase	Voltage	Current	Results
90 Degree	2.5 kV	500 A	Pass
270 Degree	2.5 kV	500 A	Pass

14 Conducted EMI

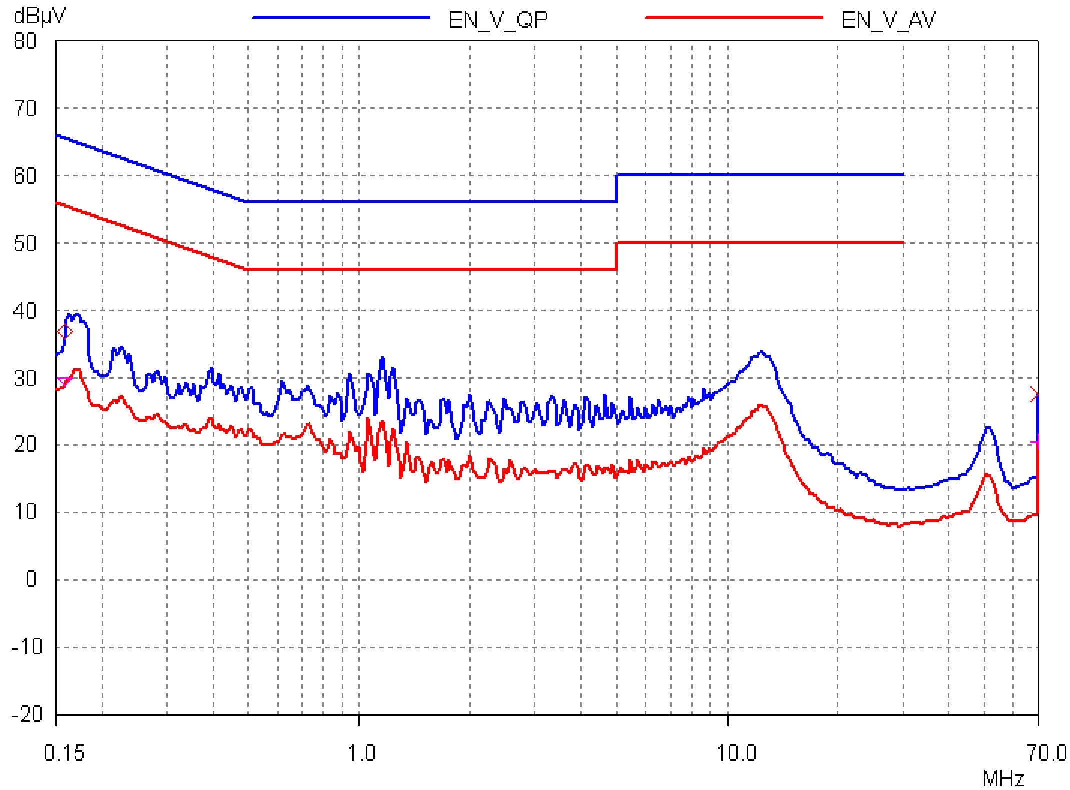

Figure 27 – Conducted EMI at 115 VAC, Output Floating. EN55015B Limits.

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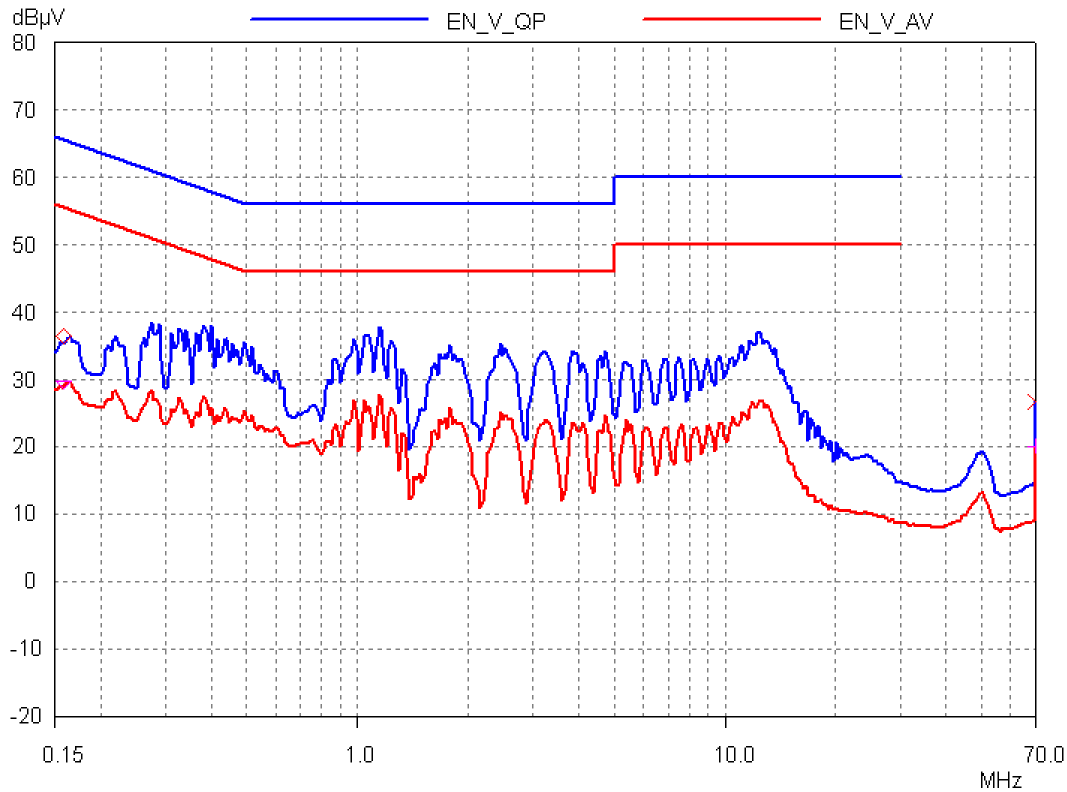

Figure 28 – Conducted EMI at 230 VAC, Output Floating. EN55015B Limits.

15 Revision History

Date	Author	Revision	Description & changes	Reviewed
15-May-08	SGK	1.0	Initial Release	JD
10-Sep-08	SGK	1.1	Updated Schematic	KM

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